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An algorithmic model for place cell emergence with robotic sensory input

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14. ABSTRACT

The hippocampus is a region of the brain used in spatial navigation. This report describes the current status of a project that has the objective of using a computational model of the hippocampus to design more robust navigation procedures for autonomous systems operating in natural environments. The report includes an overview of the problem, a synopsis of prior work in this effort, items accomplished in the work period, publications and summary conclusions. The primary item addressed in this work period was the development of a biophysically realistic computational model of a hippocampal pyramidal cell, the primary information processing unit of the hippocampus.

15. SUBJECT TERMS

Hippocampus, spatial navigation, autonomous systems, pyramidal cell, computer model

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A Novel Approach to Large Scale Brain Network Models:
An algorithmic model for place cell emergence with robotic sensor input.

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Final Report
FY 2003 Work Period

1. Overview

Biological systems demonstrate a high level of flexibility and autonomy. This project is one of a series that attempt to gain better understanding of how such biologically based solutions operate and how their organization can be exploited to improve artificial autonomous systems.

A key focus here is a long studied phenomenon in rodent navigation. Neurons in the hippocampal region of the brain, so called "place cells", have been found to individually respond to specific regions in the local environment. The organization of these cells does not show a simple topographical arrangement and the exact pattern of responses remains an active area of neuroscience investigation even now, over thirty years after place cells were first observed. The hippocampus is also known to be a key brain structure involved in learning and memory.

A novel aspect of the approach taken here is the combination of sensor information derived from a robotic platform with a biologically realistic model of the hippocampus. The intention is to allow the robotic requirements to inform any conception of hippocampal function while at the same time allowing differences between robotic navigation solutions to be contrasted with more biologically plausible schemes.

2. Synopsis of prior work

In prior work it was demonstrated that place-cell like activity can emerge from a highly reduced model of the CA3 portion of the hippocampus using limited sensory inputs from a robot. To extend this result, a more advanced (though still very limited) robot was procured. The current robot includes vision as a primary sensory modality.

A very simple and limited form of visual processing was defined to support self-localization tasks within a static environment. Pattern recognition in this context is limited to recognizing vertically oriented features, these being the most salient for self-localization tasks and also sufficient for the present work. General scene understanding is a far more complex process and well beyond the current scope.

Input to the hippocampus occurs primarily through the entorhinal cortex. How this input is encoded is not well understood except to the extent that the entorhinal cortex has cells

that are strongly influences by spatial location within a local environment but whose activity cannot be easily correlated with immediate sensory experience. The approach taken here is to extend landmark recognition such that coarsely turned place cell-like activity can be generated as inputs to the model hippocampus. While this is obviously a practical trade-off, it is also an example of how the influence of real-world sensory data can suggest factors in neural coding and network organization.

While software development is not a goal of the current work, specialized software is needed to conduct simulations of neural systems of the form considered here. Such software is especially useful in those simulations involving large networks of neurons and those involving robotic sensory inputs. Simulation software has been developed in an object-oriented fashion to facilitate expansion as research needs dictate. This software has been used to study rhythmic behaviors in large networks of simple neurons and to simulate highly detailed electrophysiological models of individual neurons.

Theoretical methods have been used to facilitate understanding of the hippocampal network and the overall function of the hippocampus, especially in the context of navigation. A common theoretical perspective on the hippocampus, based on its role in learning and memory, is one of an autoassociative memory. Such a perspective does not address roles involving sequence learning or roles directly supporting navigation. An alternate theoretical description in terms of an abstract feature map or self-organizing map was begun here and shows promise in accounting for aspects of the hippocampus not addressed in other theories.

The dentate gyrus is a highly organized layer of cells that provides inputs to a further layer in the hippocampus, that is, to CA3. A theoretical role has traditionally been assigned to the dentate gyrus in the context of an autoassociative memory system as a technique of pattern separation. For this work, however, an alternative approach was investigated. Based on unique properties of dentate gyrus anatomy, a model was developed suggesting that the dentate gyrus may play a more direct role as the front-end of a process for recognizing complex patterns. A poster on this topic was presented at CNS2002 and a follow-on paper on the topic has published in this work period.

An integral component in learning is the plasticity found in synaptic connections between neurons. In a number of brain regions, including the hippocampus, a form of plasticity based on highly exact timing relationships between inputs and the output of a neuron has been found (spike-time dependent plasticity or STDP). In the sense that there are common themes to self-organization within the brain, this form of plasticity may well be one. Current neural models of the hippocampus do not include this form of plasticity. For this work, development of a more comprehensive model including this form of spike-time dependent plasticity was begun but has not yet been completed.

3. Items accomplished in FY2003 work period

Networks of simple cell models have been explored both in this work and by other researchers. While some aspects of hippocampal network behavior can be studied

through such models, experimental results suggest that real cells have a much more elaborate set of behaviors than would be indicated by these simple models, especially in the areas of synaptic integration, plasticity, and neuromodulation. More detailed and realistic cell models are needed from which to form the overall hippocampal network model.

For this reason, work items related to developing a realistic cell model were considered to be of highest priority and became the primary focus of activity during this work period.

To better model cellular behaviors, prior models of hippocampal pyramidal cells were reviewed. One of these, a CA3 pyramidal cell model developed by Traub et al. in 1994, was implemented in the current simulation software and reviewed for use here. However, a large number of experimental results have arisen since the original development of the Traub model and updating it proved impractical because of differences between the new findings and the underlying assumptions used in the original model definition.

To directly incorporate newer experimental findings, especially those involving channel distributions and plasticity, a new family of hippocampal pyramidal cell models was defined for this work. This model is based on realistic reconstructions of cellular morphology, new measurements of channel properties in dendrites, and new measurement of channel distributions in dendrites. One complex part of model development is combining multiple experimental measurements in a way that aggregate cell behavior can be reproduced in the model. In its current state, the pyramidal cell model attempts to reproduce behaviors most relevant to the current work and is not necessarily intended to be a complete model of all cell behaviors. The model was presented as a poster at SFN 2003.

A side effect of developing a more complex cell model was the need to improve simulation methods. A new variant of prior differential equation solution methods for compartmental models was implemented in the simulation software. This method combines the standard Crank-Nicolson method with Richardson extrapolation for error control of variable time step sizes. While this new method offered a significant improvement over the performance previously available, it became apparent that available computational resources would not support a network of detailed cell models.

Rather than attempt what would otherwise be two different but overlapping models, one a detailed cell model and the other a network model of simplified cells, an alternative approach was defined. For present purposes, it is sufficient to simulate a single target cell using a biophysically detailed model. All cells providing inputs to the target cell can be treated as generating randomly generated spike trains with known statistical properties. This approach allows the target cell to have the full richness of cellular morphology, channel distributions, and plasticity, while retaining control over the simulation complexity. Such a combination should yield a result that is both more scientifically valid and also far less computationally expensive.

For consistency of testing, inputs can be generated using a simulation of the robot sensory data. There is no reason in principle that full robotic sensory data cannot be incorporated using sensory preprocessing as previously defined, but the overall level of complexity in the simulation suggests that this should occur as a later step.

As of the end of the current period, development of the necessary model and simulation software is well underway but remains incomplete.

4. Publications

The following were published or presented in the current work period:

Baker JL (2003) Is there a support vector machine hiding in the dentate gyrus? Neurocompting 52-54: 199-207.

Baker JL and Olds JL (2003) Emergence of a well-formed pyramidal neuron electrophysiology from a simple, biologically plausible computational model. Society for Neuroscience Abstract, Program No. 377.21.

Copies of these publications and updated technical memoranda are available under separate cover.

5. Conclusion

Development of a meaningful model of a biological system is a complex undertaking. As originally formulated the project has been ambitious, but there is a reasonable expectation that the model can be extended to a degree that useful results can be derived.

How these results will be utilized in the design of autonomous systems remains an open question. Biological systems express a staggering degree of complexity. The computational burden of simulating a single cell, even at a coarse level, suggests that biological systems employ methods that are not easily duplicated using current engineering practices, at least not by direct simulation.

However, one should not lose sight of demands on biological systems that may not apply to an artificial system. In general, biological systems are self-constructing, self-organizing, self-maintaining, self-reproducing, operate using miniscule power, operate with inherently unreliable components, and are highly evolvable. Artificial autonomous systems need not have all these properties to be useful. Being able to adapt biological organization methods to exploit massive parallel operation at even a fraction the scale of a biological system would be a significant step in the engineering of artificial autonomous systems. The present work is only one step towards that objective.